ELSEVIER
Agriculture, Ecosystems and Environment 88 (2002) 147–152
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Biological control as a means of enhancing the sustainability of crop/land management systems

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Abstract

Biological control can contribute to the sustainability of crop/land management systems by reducing the inputs currently derived from non-renewable fossil energy sources. Biologically based technology will have to be developed and gradually integrated into management systems that will include some chemicals for a long time to come. A researchable paradigm is presented: using "weed-suppressive soils" for biological control of weeds in crops. This example requires extensive knowledge of the ecology of soil microflora and how various populations are affected by management strategies. These management strategies are structured to foster microbial populations in soils that will provide timely suppression of early flushes of annual weeds. Biological seed treatments using microbial antagonists will have to be developed to "safen" the crop against the active biological factors in the "weed-suppressive soils". As these and other biological alternatives are adopted, the concept of "sustainability" will move closer to reality.

Keywords: Soil-borne pathogens; Bare-patch disease; *Rhizoctonia solani*; Grassy weeds; Wild oats; *Avena fatua*; Downy brome; *Bromus tectorum*; Jointed goatgrass; *Aegelops cylindrica*

1. Introduction

Generally, "sustainable agriculture" is considered to be a system of agriculture that can be maintained or prolonged. An appropriate question is: What kind of time frame is reasonable for consideration in developing such systems? Eugene Shoemaker, geologist emeritus with the United States Geological Survey, outlined the dangers of asteroid collision to earth (Boudreau, 1994). Although bits of metal and rock strike the earth's atmosphere every month, Shoemaker noted that an asteroid about a half-mile in diameter, one large enough to cause widespread climate changes, strikes the earth every 100,000 years. Although 100,000 years is probably too long for consideration, some problems with agriculture are just as critical and much more imminent.

Many Land Grant Universities in the United States recently celebrated their 100-year anniversaries and reflected on their contributions to agricultural science in that period of change during a technological revolution. The nation's agriculture went from scythes to horsedrawn reapers and steam-powered threshers and then to modern self-propelled combines, from pitchforks to balers and mechanical hay bale loaders, and from hoes to herbicides.

Now an appropriate question is: What can science provide toward sustainability of agriculture in the

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PII: S0167-8809(01)00251-1

next 100 years? Changes in society and changes in the environment now occur so rapidly that plans for any agricultural research activity rarely go beyond 10 years, and many grant proposals/awards are limited to 3 years. The Agricultural Research Service (ARS) develops its "strategic plans" for 6-year periods while individual research programs are generally planned for three to 5-year periods and then subjected to review. Forty-year veteran ARS scientists will go through at least eight project reviews during their careers. If, within a career, each scientist contributes something to the ability of the nation to "maintain or prolong" its agriculture, then ARS will have made progress toward its mission of ensuring food and fiber for the United States.

The agency's effort to develop "sustainable biological control of weeds" contributes substantially to that mission. One of the major reasons for that has to do with the use of energy in agriculture. In general, the very productive system of agriculture in the United States cannot be prolonged unless changes are implemented soon.

A peasant in a "third world country" is actually more efficient in some ways than a modern day Great Plains farmer in the United States. The peasant gains 10 calories of energy in production for one calorie of labor while the Great Plains farmer spends 10 calories of non-renewable fossil energy to gain 1 calorie in production. However, a Great Plains farmer has such an abundant supply of non-renewable energy that he or she produces 600 times more than does the peasant. By borrowing against the principal in our non-renewable energy capital, <2% of our population is required in production agriculture (Rifkin, 1980).

However, the interest costs are high. The fossil energy dedicated to weed control serves as a good example. Of all petrochemical pesticides, herbicides are used in the greatest volume. Herbicides accounted for 44% of the total, insecticides for 29%, fungicides for 21%, and others for 6% (Klassen, 1995).

It should be noted that herbicide residues do not pose a threat to our food supply; those problems come mainly from insecticides and fungicides on fruits and vegetables. Nevertheless, in some cases, herbicides are a risk to the environment. For example, the effect of herbicides on the safety of water supplies is intensifying interest in alternative management strategies (Vangessel et al., 1996). Moreover, herbicides often cause damage to non-target vegetation. An entire for-profit industry exists to examine spray drift damage to crops and prepare reports for lawyers representing farmers and commercial applicators in legal suits. None of this contributes to sustainable agriculture.

Another important aspect of herbicide use is the development of resistance in weeds to specific chemicals. For several years early in the development of herbicides, examples were unknown for weed resistance to the chemicals. Insects developed resistance to insecticides much earlier. But now, more than 300 examples of resistance are known for various weed species to various herbicides. If developing sustainable agriculture means reducing non-renewable inputs, then a need exists to develop sustainable biological control of weeds.

Thus, the objectives of this paper are to: (1) provide some historical background; (2) present a new paradigm that describes some situations where and how biological control potentially can be integrated into farm or ranch management systems and (3) outline some current constraints and pressures that will affect the future development of biological control of weeds. The focus is on weeds, however, the same principles apply to biological control of insect pests and crop pathogens.

2. Historical perspective: biological control of weeds in crops

Biological control is generally accepted as an appropriate method of managing weeds on rangeland and in other non-cropland areas such as aquatic sites. In these non-cropland situations, "classical" or "introductory" biological control is employed. In this approach, the natural enemies of the alien target weed are found in the weed's land of origin, evaluated for host specificity, and approved by the Animal and Plant Health Inspection Service, USDA for open field release. This method, if successful, has several advantages: (1) the biological control agents are self perpetuating; (2) the agents can suppress weeds on lands too rough to spray with a ground rig; (3) the agents will spread on their own after initial establishments and (4) one-time costs can be amortized over years and area. However, the main disadvantage is that once released, the agents cannot be recalled. That is why great care is taken to consider potential conflicts of interest, non-target effects, and host range data before release.

One excellent example of implementing the "introductory" or "classical" method of biological control is that of the European invader, leafy spurge (*Euphorbia esula-virgata*), in Montana, USA (Rees et al., 1996). This method employs various European spurge-eating species of *Aphthona* fleabeetles, the stem-boring beetle, *Oberea erythrocephala*, and judicious short-term sheep-grazing of the spurge. Combining these "biological controls" allows the release of perennial grasses that support a large cattle industry.

An alternative approach is generally considered for biological control of weeds in crops because cultivation can potentially disrupt life cycles of introduced "classical" biological control agents. This alternative approach is the augmentation of extant biological control agents. Most of the research effort for augmentative biological control of weeds in crops in the last 20–25 years has been directed toward development of "native weed pathogens" (NWPs). These are known in the literature as "mycoherbicides" (fungi used as herbicides) or as "bioherbicides" (fungi or bacteria used as herbicides).

Two notable NWPs were discovered and successfully developed in the 1970s and early 1980s (Quimby and Birdsall, 1995). They could be cultured artificially and applied much like herbicides in the field with good control of the target weeds. These were "DEVINE", *Phytophthora palmivora* for control of stranglervine (*Morrenia odorata*) in citrus, developed by Abbott Labs; and "COLLEGO", *Colletotrichum gloeosporioides* f. sp. *aeschenomene* for control of northern jointvetch (*Aeschenomene virginica*) in rice and soybeans, developed by Upjohn. Both products were registered and labeled by EPA in the early 1980s. The development of these two products generated much interest in research that has persisted to the present. COLLEGO was especially exciting because good weed control could be obtained with 2.5 l of fermentation product per hectare.

USDA's Agricultural Research Service established projects to work on NWPs at Stoneville, MS; New Orleans, LA; Frederick, MD; and Peoria, IL. State Agricultural Experiment Station scientists from coast to coast, from north to south, and foreign scientists, including Canadians, Australians, Britons, Israelis, and Japanese, started projects in this subject area. A Southern Regional Research Project, first S-136, then S-234, and later S-268, was initiated by the Cooperative State Research Service on "Biological Control of Weeds with Plant Pathogens". Generally, more than 30 scientists have attended the annual meetings. Industry has also been well represented each year. The project has the main objective to discover new NWPs and, through cooperation with industry, to develop of the NWPs into commercial products.

Although many new NWPs have been found and characterized, only one new product, other than the original two, has been registered in recent years. This was "BIOMAL", *C. gloeosporioides* f. sp. *malvae*, registered in 1992 by Philombios in Saskachewan, Canada for control of round-leafed mallow (*Malva neglecta*) in wheat, field peas, and other crops (Quimby and Birdsall, 1995).

At the meeting of S-234 in April 1994, it was reported that "DEVINE" and "COLLEGO" were no longer being produced because the markets were too small. Although representatives of industry were present, interest in NWPs had apparently waned. Possible reasons for their loss of interest included the following: (1) most candidate NWPs have been of too narrow host range for economic use — other weed species in the same field(s) also need to be controlled; (2) herbicides are still available to control some of the target weeds more effectively and economically than do the NWPs; (3) several herbicide-resistant crops have been developed through genetic engineering and (4) production, formulation, and shelf life of products are continuing problems for most candidate NWPs (Quimby and Birdsall, 1995). For these reasons, a new paradigm is required to revitalize interest in biological control and to incorporate it into weed management systems for crops.

3. A new paradigm: using weed-suppressive soils for biological control of weeds in crops

If biological control is to be integrated into a sustainable weed management system for agronomic crops, then certain requirements will have to be met: (1) the biological control component will have to be compatible and complementary to the other components of the system; (2) producers should find the biological control easy to use; (3) the biological control will have to be reliable, repeatable, and economical and (4) the biological control should contribute to the sustainability of the management system by reducing inputs of non-renewable resources and otherwise aiding in the conservation of soil and water resources.

A no-till system for a spring-seeded crop is offered as an example of where a new paradigm might be applied in the Great Plains. The system proposed for this area involves the management of the soil microflora to foster the suppression of annual weeds in spring-seeded wheat or barley under a no-till regime. Dr. William Grey of Montana State University has coined the following term for this concept: "Management of Weed-Suppressive Soils". Commonly, producers treat the lush winter annual weeds with non-selective glyphosate (isopropylamine salt of *N*-phosphonomethyl glycine) herbicide before planting. Hudak (1992) showed that this herbicide treatment induces a "pulse" of *Rhizoctonia*, a soil-borne plant pathogen that builds up on the dying roots of the winter annual weeds. If the farmers plant immediately into that "pulse" of *Rhizoctonia*, then the pathogen will bridge to the crop and produce a disease known as "bare patch" of wheat or barley.

King (1998) conducted preliminary greenhouse experiments to quantify the effects of bare-patch disease against barley and selected grassy weeds. The fungus, *Rhizoctonia solani* AG-8, was grown on autoclaved whole oats and applied to pasteurized soil at 1 and 5 wt.%. Test plants were seeded into pots containing soil charged with inoculum or into pots with untreated soil (controls). The soil-borne *R. solani* G-8 at the 1% inoculum level reduced shoot dry weights after 6 weeks for barley, wild oats (*Avena fatua* L.), and jointed goatgrass (*Aegelops cylindrica* Host) from 20 to 30% (Table 1). Increased inoculum at 5% did not enhance the reduction in shoot dry weights nor did either rate significantly reduce shoot dry weights of downy brome (*Bromus tectorum*) or seedling emergence rates for any of the test species (data not shown). The results with downy brome corresponded with previous research (Grey et al., 1995).

The King (1998) study also included a preliminary field trial conducted using autumn inoculation of winter wheat (as a simulated cover crop of weeds) with *R. solani* strains grown on previously autoclaved whole oats as in the greenhouse trial. Control plots were treated with equivalent amounts of killed fungal inoculum (autoclaved). In the spring, the winter wheat was sprayed with glyphosate and the plots were planted to spring barley or cultivated oats. Mean seed weights of harvested barley and oats were reduced more than 20% from plots treated with live inoculum compared to seed weights from plots treated with killed inoculum.

Table 1
Growth suppression of barley, wild oats, and jointed goatgrass by *R. solani* AG-8 (inoculum) on autoclaved whole oats

Grass species	Inoculum	Shoot dry weight (mg per plant)	Percent of control (%)
Barley	Control	790	100
	1%	618	78*
Wild oat	Control	833	100
	1%	670	80*
Jointed goatgrass	Control	847	100
	1%	594	70*

* Significantly different from control ($P = 0.05$).

To prevent "bare patch", producers have to wait two or 3 weeks to plant or they must till the soil to reduce the pathogen. Presently available chemical fungicide seed treatments are effective against this disease, but these must be annually applied to give control and this adds additional cost to grain production. If producers have to till the soil, then the advantages of increased water retention and organic matter in the no-till system are lost.

The system envisioned here includes a need to develop effective biological seed coatings that will protect the crop against *Rhizoctonia* even when planting occurs immediately after glyphosate treatment. Cooperative exploration in foreign lands for effective antagonists as seed coatings could be a productive area of research. With effective seed treatments producers can take advantage of "pulses" of plant pathogens in the soil to suppress annual weeds that might otherwise germinate and emerge about the same time as the crop. The idea of seed treatments is not new (Harmon, 1991), but we are proposing combining crop seed treatments with management strategies that foster weed-suppressive soils.

O'Donavan et al. (1985) have observed that just 4–5 days lead in growth by the grain crop will allow it to develop a competitive advantage that will actually reduce or even eliminate seed production by wild oats. If producers could exploit the "pulse" of *Rhizoctonia* to suppress weeds such as wild oats for just a few days while at the same time achieving optimum crop seed germination, emergence, and growth, then such lead-time in growth by the crop with the associated competitive advantage may be realized.

The saving of non-renewable resources and major contribution to sustainable agriculture in this case would be to reduce the need to apply selective, post-emergence herbicides for control of wild oats in the grain crop. In this model, the producer actually will be growing the biological control agent on the roots of the dying winter annual weeds. A new input will be a seed treatment, but this will be more than offset by reducing the overall use of herbicides and trips required to apply them across the field.

Other models can no doubt be developed for managing the soil microflora to suppress weeds in other crops. However, if the model described in this paper can be successfully developed, it will go a long way toward enhancing the sustainability of culturing some of the major crops included in the agriculture of the Great Plains.

4. Development of biological control of weeds in crops: current and future pressures

Current pressures are producing increased support within USDA agencies for biological control research. In a period from 1988 to 1994, the Agricultural Research Service had lost about 20% of the scientists in biological control of weeds because of retirements and reassignments (1994, J.R. Coulson, Director of Biological Control Documentation Center, USDA-ARS, personal communication). These vacancies are now being filled because of changing priorities in the agency. In 1997, ARS redirected US$ 15 million from research on chemical control to biological control and ecology of weeds. This area of research is now recognized as a means of searching for ways to provide alternatives to agricultural chemicals that are under attack from a number of fronts. Agricultural producers cannot give up their chemical tools for pest and weed control until research provides them with viable alternatives. Otherwise, urban oriented societies could well starve.

Pressures will undoubtedly continue into the future to reduce the use of non-renewable pesticides, including herbicides. Consumer orientation is definitely in that direction. Hopefully, these pressures will result in yet more support for the research that will be required to develop the biological alternatives. There will probably be a gradual transition with biological components, as they become available, being integrated into management systems that will include some chemicals for a long time to come. As the biological alternatives become an increasing part of major agricultural management systems, the concept of "sustainability" will have a chance of becoming reality.

5. Conclusions

The concept of "sustainability" in agricultural systems dictates that inputs currently provided by non-renewable petrochemical resources be replaced by biologically based renewable inputs. Herbicides constitute the major share of pesticides sold (44%). Replacing petrochemically based herbicides with renewable NWPs, augmented and applied like herbicides, will require decades of research on production, stabilization, formulation for shelf life, and development of application methods.

An alternative paradigm could involve the induction of "weed-suppressive soils". Some "burn down" pre-plant herbicides in no-till systems apparently foster the development of pulses of soil-borne pathogens on dying roots of winter annual weeds. These pathogens can create problems such as "bare-patch disease" in cereal crops planted too soon after the burn down treatment. The paradigm for employing the pulses of soil-borne pathogens for weed suppression would necessitate a pro-biotic approach by the treatment of crop seeds with microbial antagonists.

The paradox of this system is that a petrochemical, glyphosate, is employed pre-planting to kill the annual winter weeds. Thus, further refinement toward renewable inputs would be to use a "cocktail" of broad-spectrum plant pathogens augmented and applied for the pre-plant "burndown" of the winter annual weeds. In some cropping systems, the use of winter annual living mulches that die off as warm weather approaches could provide inducement to soil-borne pathogens. Again, the principal crops would have to be protected with seed-applied antagonists. These various components of the weed management system could benefit from research in genetics, either traditional or transgenetics. For example, increasing resistance in the crop(s) to the soil-borne pathogens with traditional plant breeding might decrease the need for seed treatment without reducing the marketability of the crop. Genetically modifying living mulches for early senescence could provide earlier "release" of the crop.

This new paradigm of utilizing induced soil-borne microbes for weed suppression would be compatible, integral, and complementary to no-till crop management systems. Producers should find this biological control easy to use; it would require very little change in current practices except that it should reduce the need and costs for post-emergence herbicides.

All of these refinements toward "sustainable" weed management with biologically based systems will require their own quota of research and development to ensure reliability and repeatability. A major component of the research will be the expansion of knowledge on the ecology of soil microbes in various crop and weed management systems. The overall result will be conservation of soil and water with fewer non-renewable inputs.

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